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(54) **LENS MANUFACTURING METHOD**

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B24B 41/06 (2012.01)
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CPC ***B24B 13/01*** (2013.01); ***B24B 13/005*** (2013.01); ***B24B 41/06*** (2013.01); ***B24B 49/04*** (2013.01); ***B24B 49/06*** (2013.01)

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See application file for complete search history.

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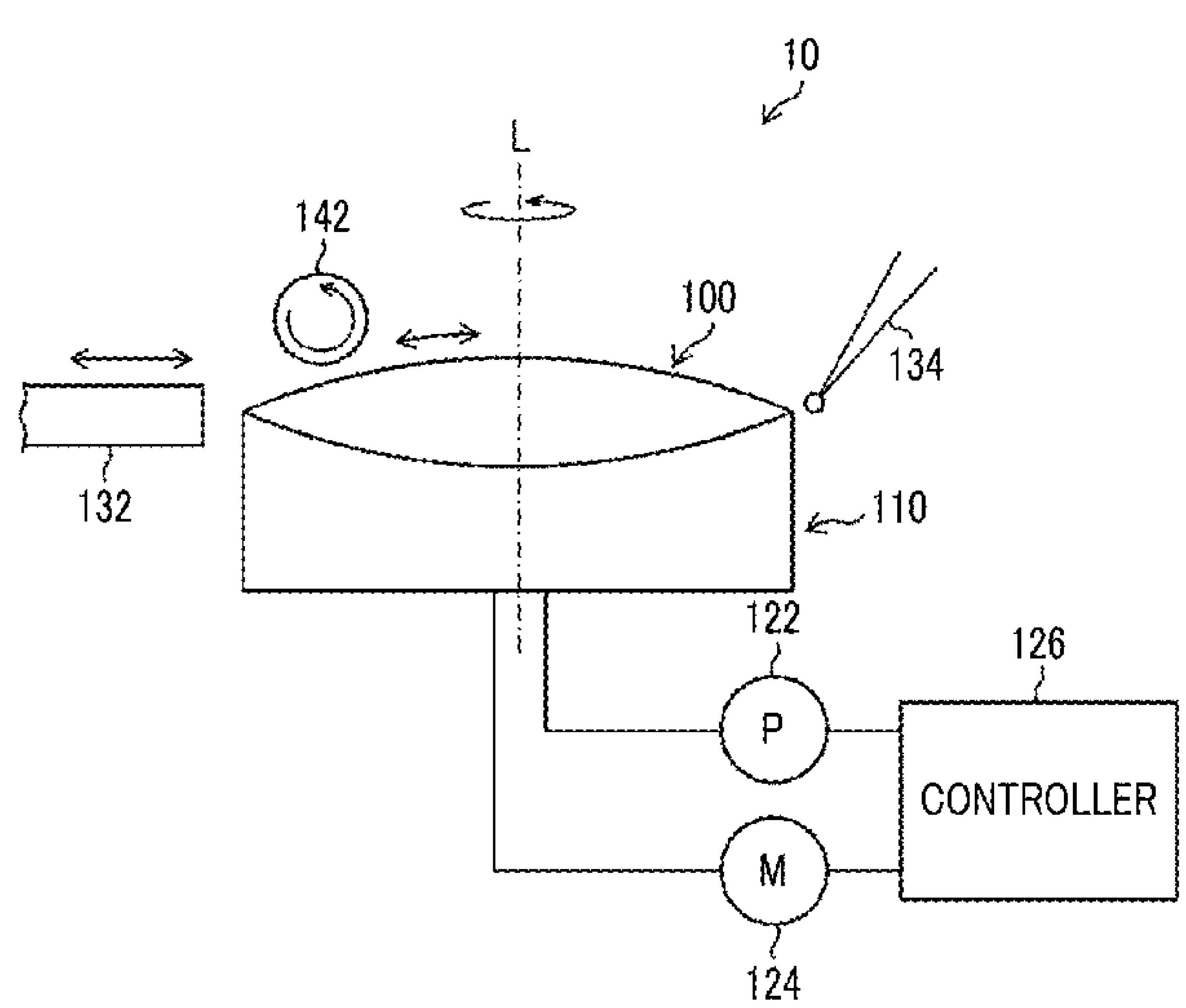
(57) **ABSTRACT**

A lens manufacturing method including a holding step of holding a lens in a lens holding fixture, and a machining step of machining a surface to be machined in the held lens. A reverse surface of the surface to be machined is machined into a non-planar shape with a first surface shape error. A lens holding surface of the lens holding fixture is machined into the same shape as the non-planar shape with a second surface shape error smaller than the first surface shape error. In the holding step, the reverse surface is brought into surface contact with the holding surface in imitation of the holding surface to correct the shape of the lens such that the reverse surface runs along the holding surface. In the machining step, the surface to be machined is machined in a state where the correction has been made by the holding step.

8 Claims, 13 Drawing Sheets



(51) **Int. Cl.**
B24B 49/04 (2006.01)
B24B 49/06 (2006.01)
B24B 13/005 (2006.01)

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FIG. 1

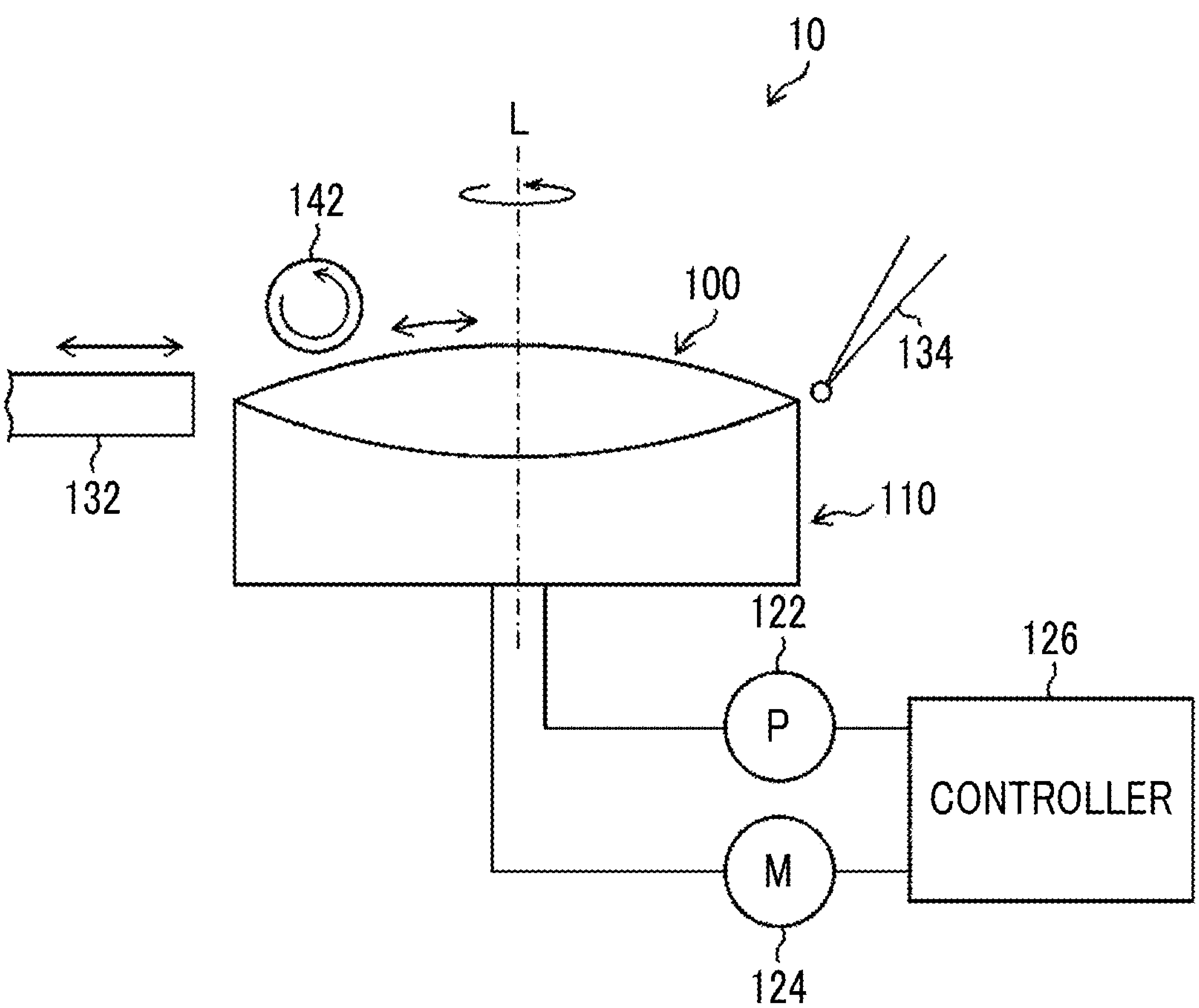


FIG. 2A

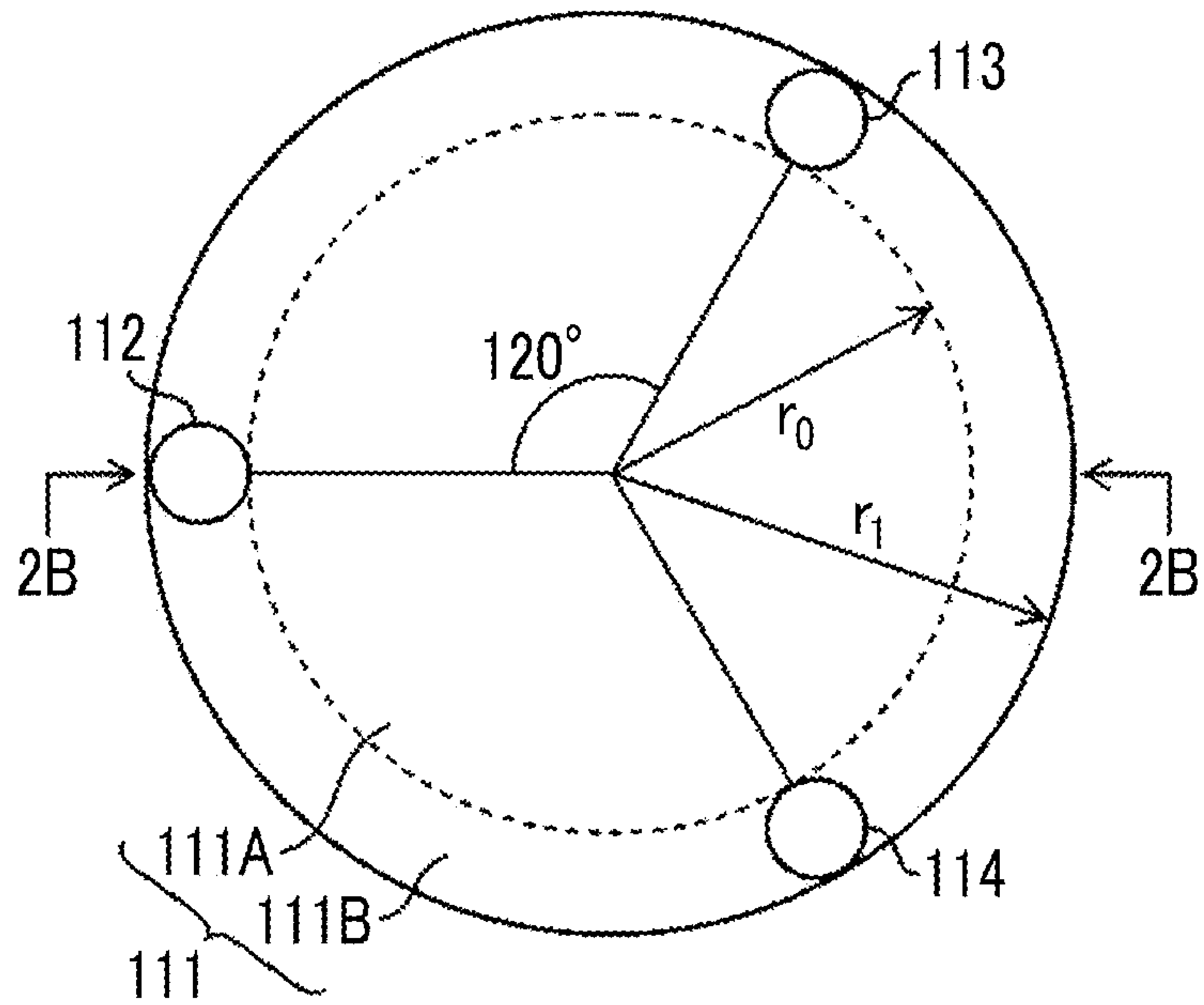


FIG. 2B

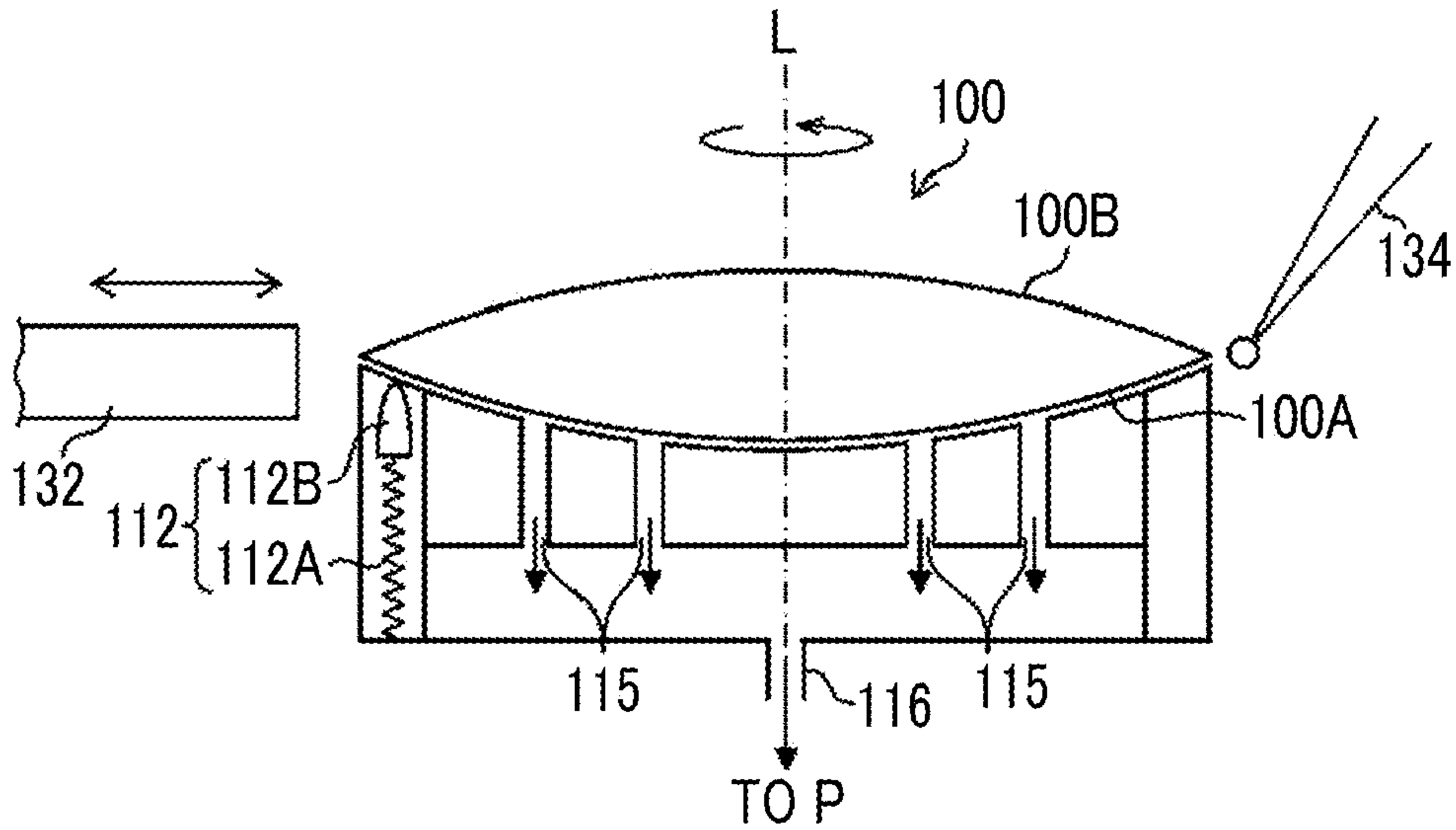


FIG. 2C

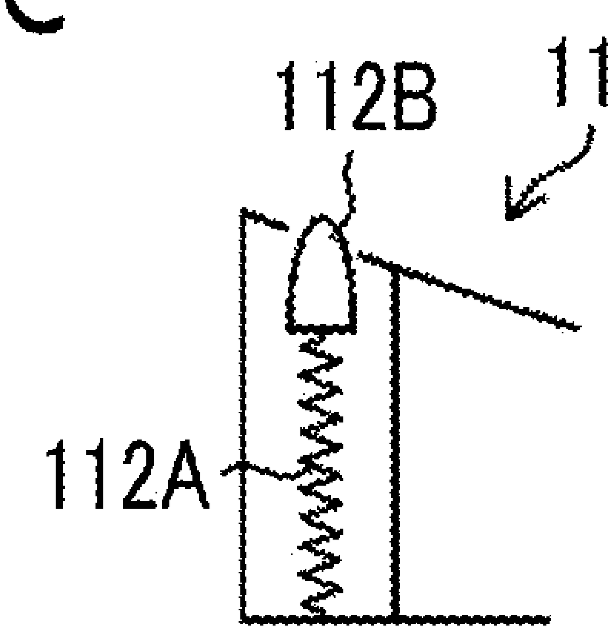


FIG. 2D

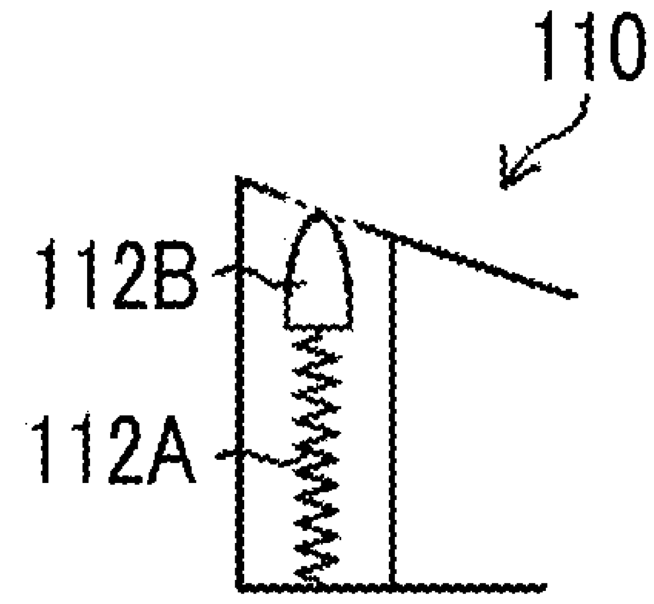


FIG. 3

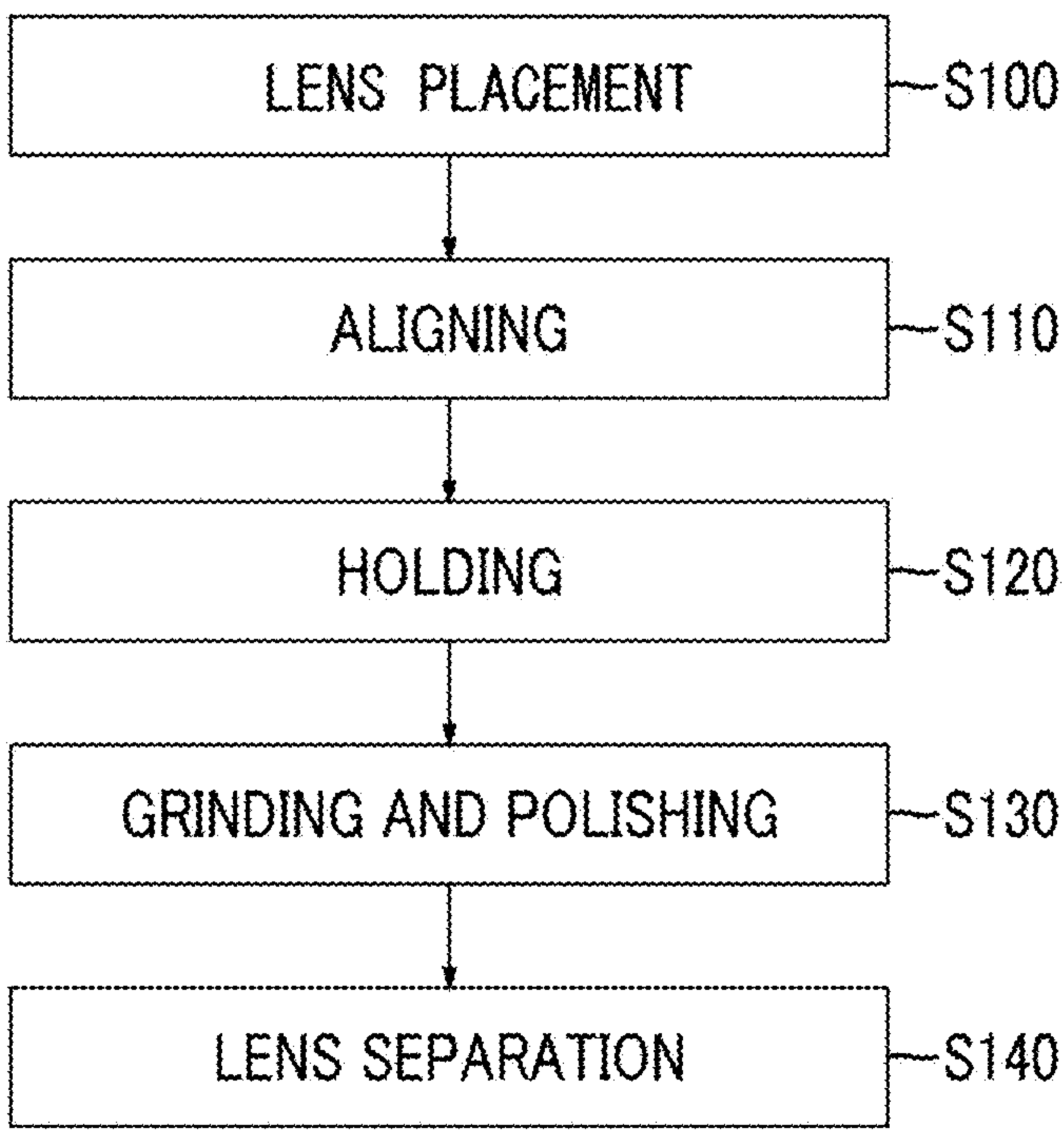

LENS PLACEMENT
S100
ALIGNING
S110
HOLDING
S120
GRINDING AND POLISHING
S130
LENS SEPARATION
S140

FIG. 4

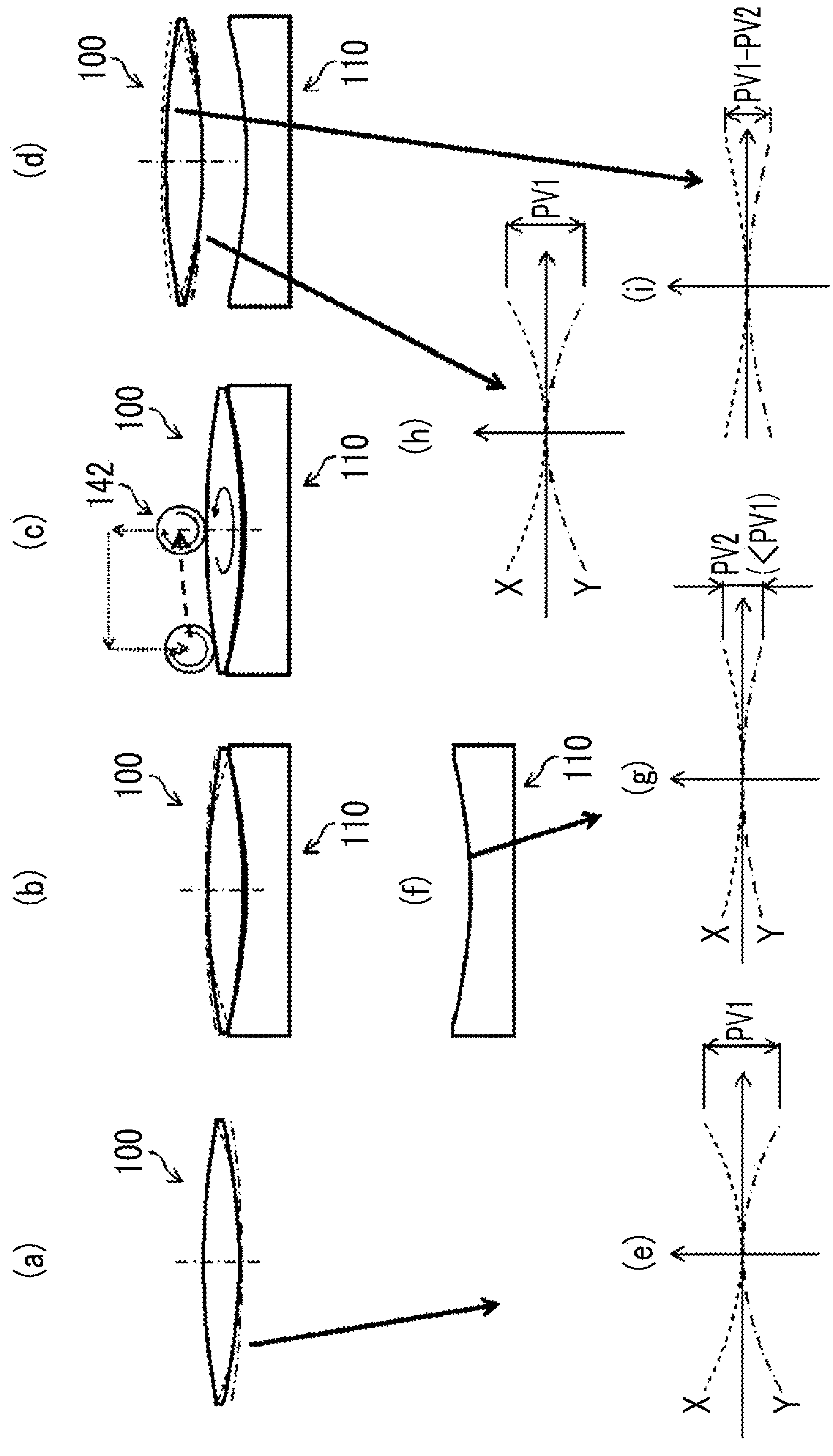


FIG. 5A

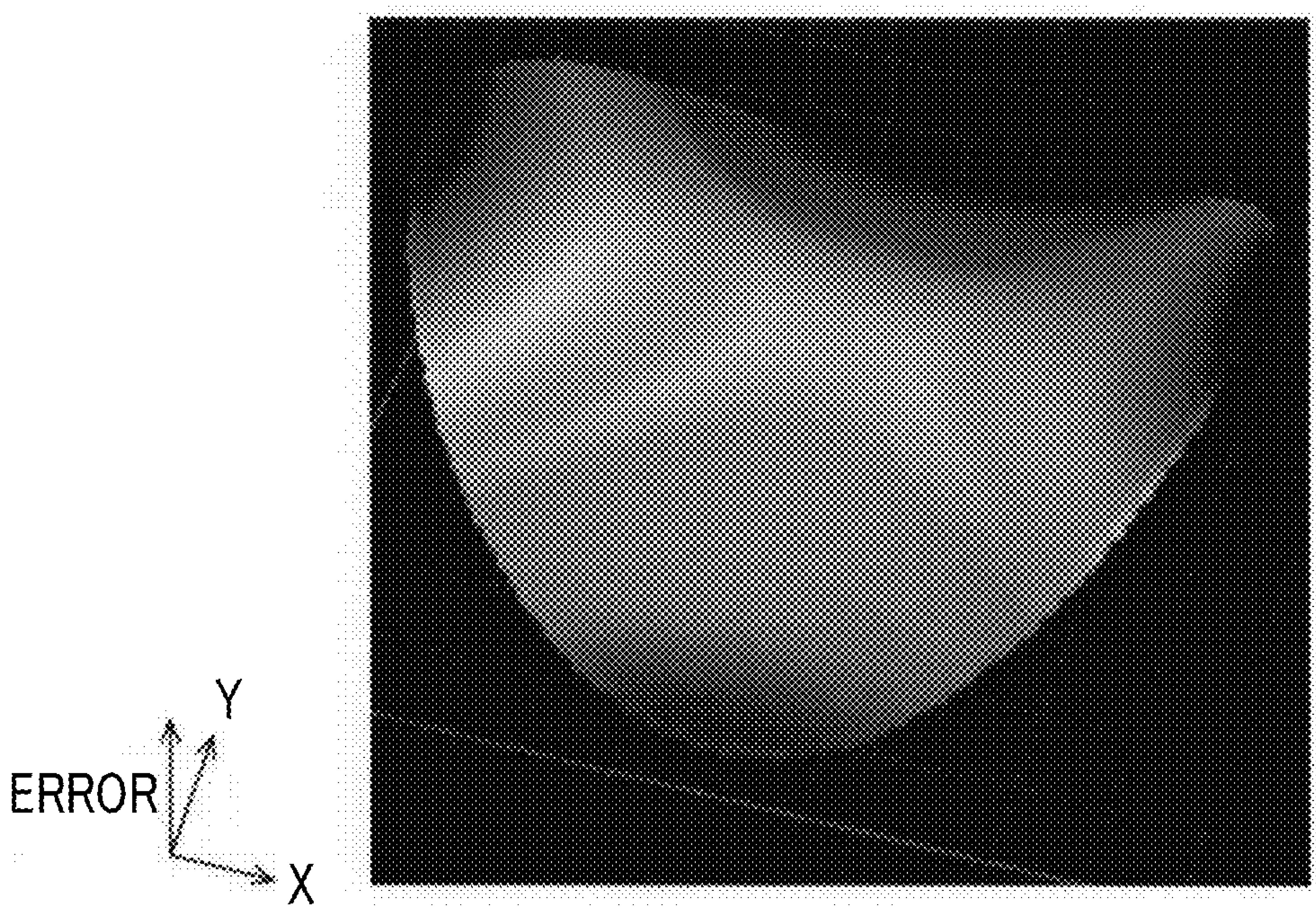


FIG. 5B

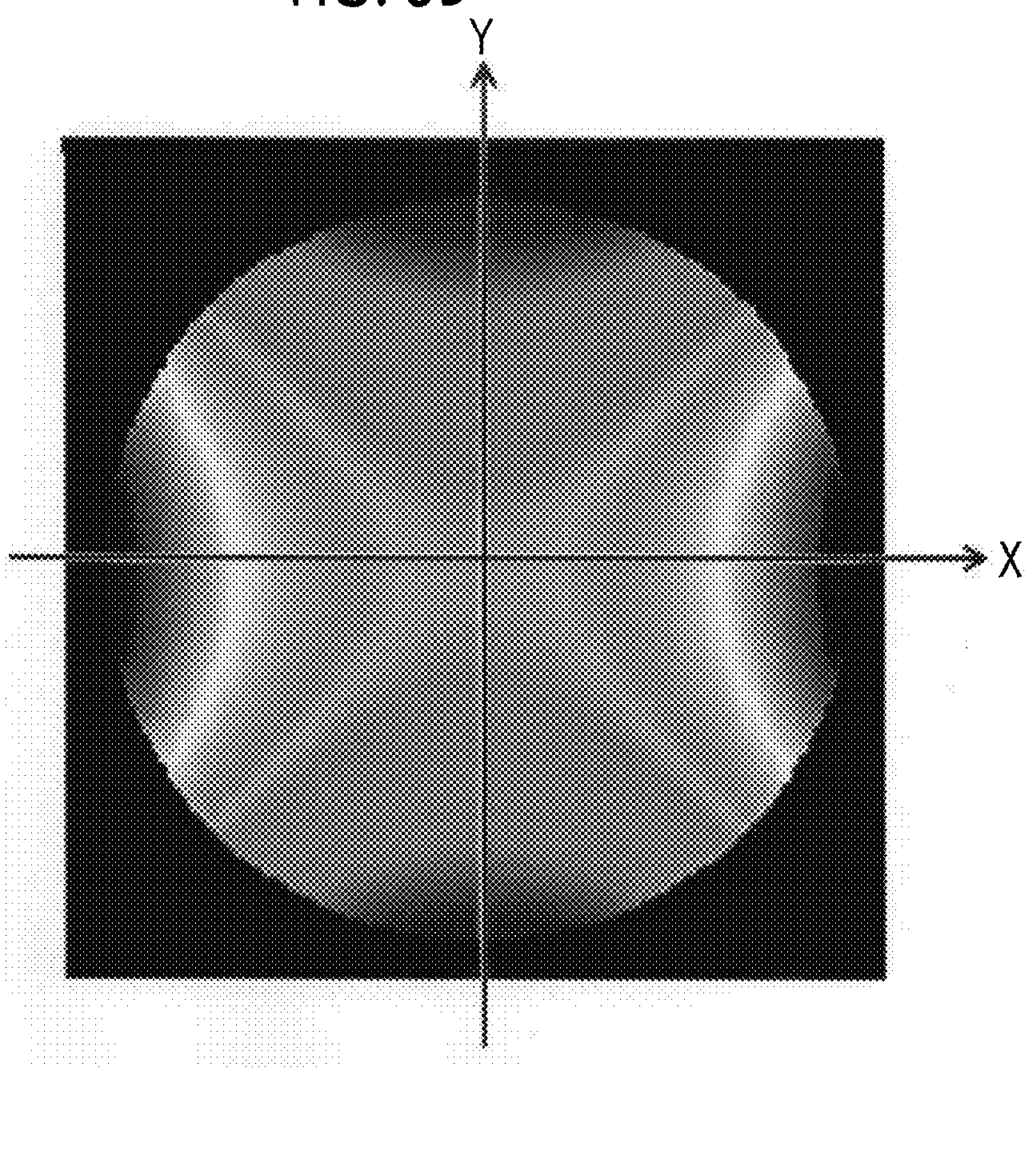


FIG. 6

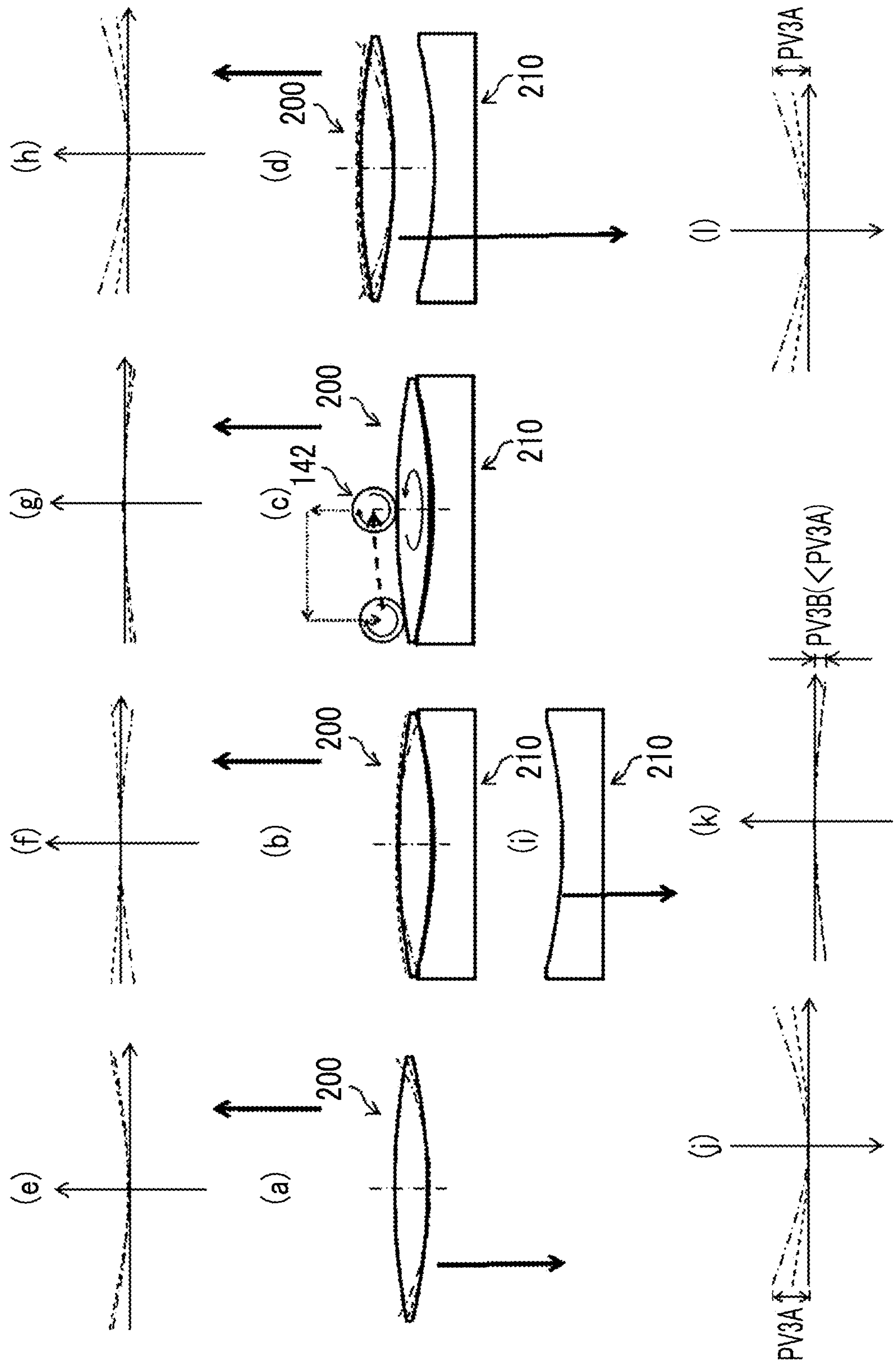


FIG. 7

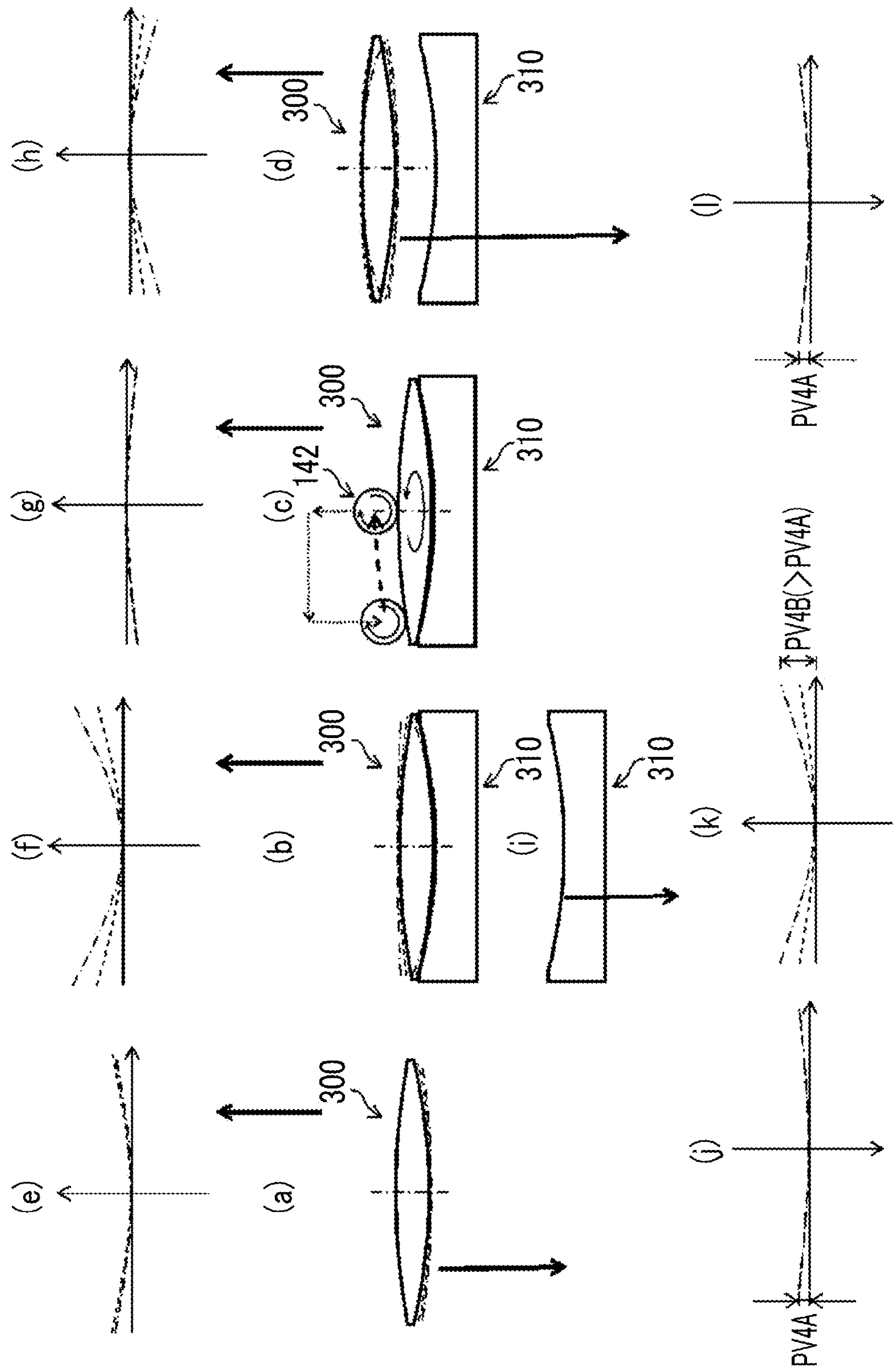


FIG. 8

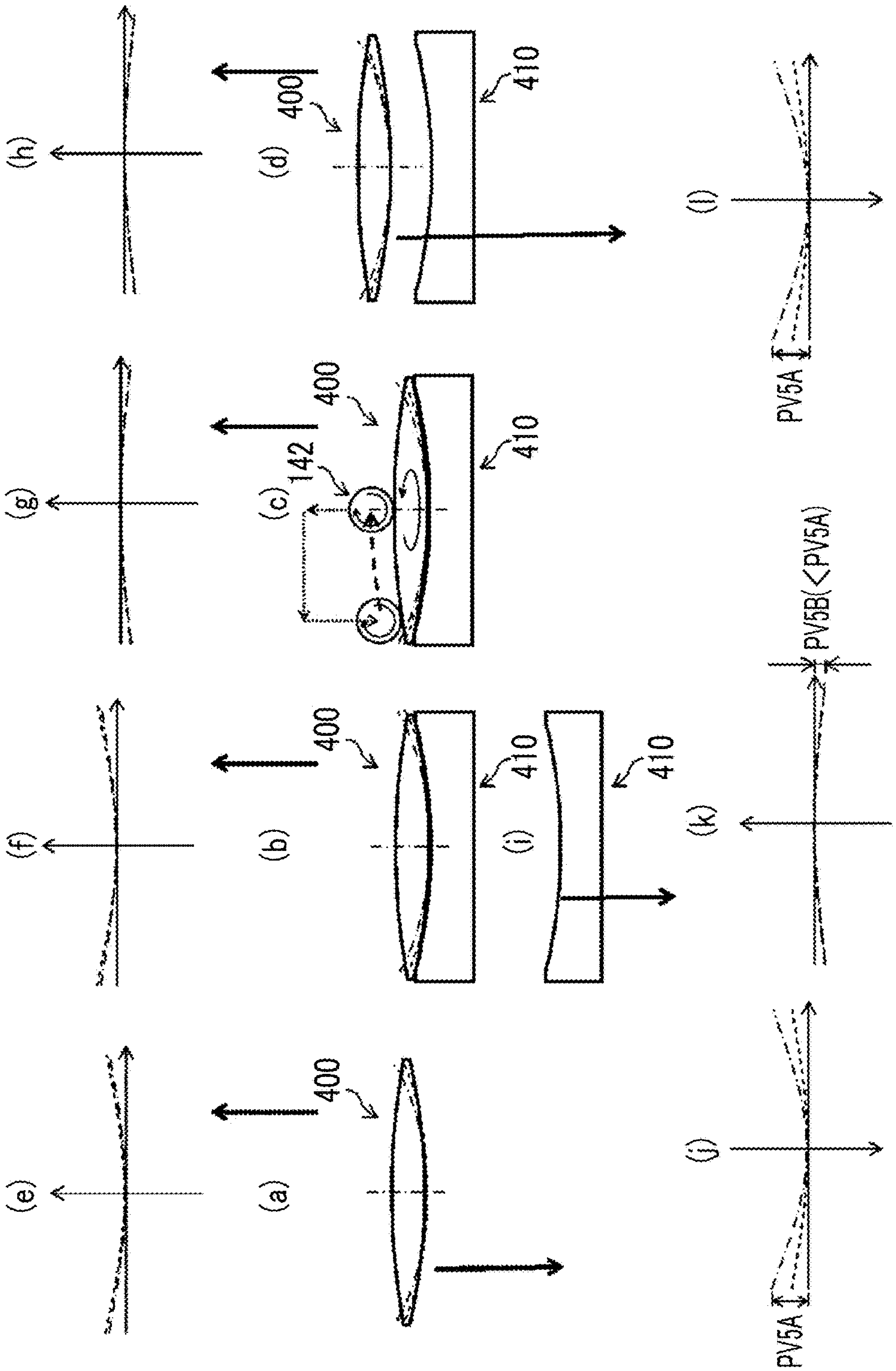


FIG. 9

	REVERSE SURFACE ASTIGMATISM ERROR	HOLDING FIXTURE SURFACE ERROR	TRANSMISSION WAVE SURFACE ABERRATION
EXAMPLE	150nm	30nm	25nm
COMPARATIVE EXAMPLE 1	50nm	200nm	190nm
COMPARATIVE EXAMPLE 2	180nm	30nm	140nm

FIG. 10

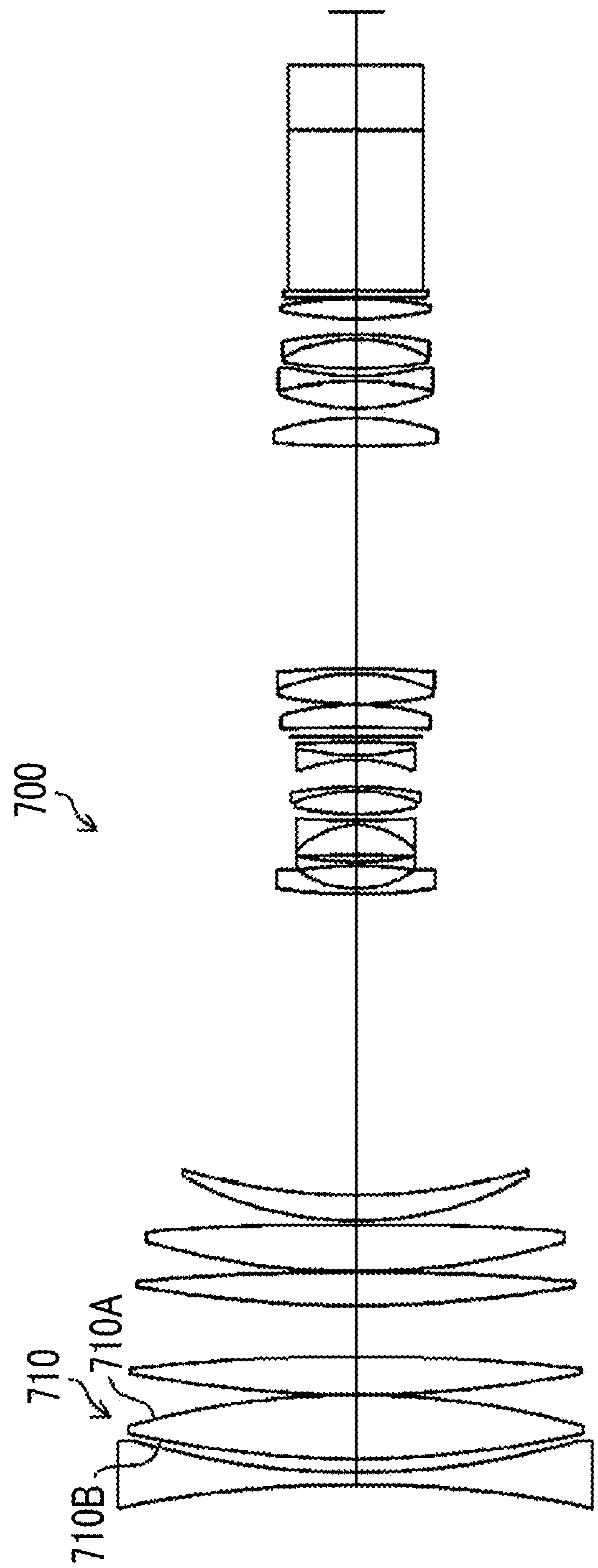


FIG. 11A

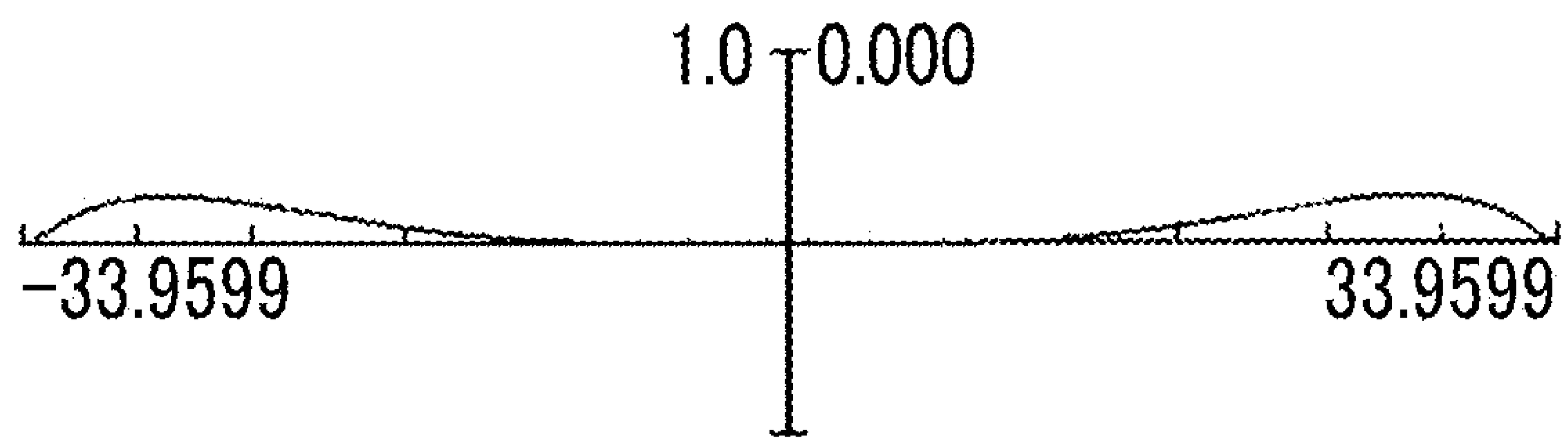


FIG. 11B

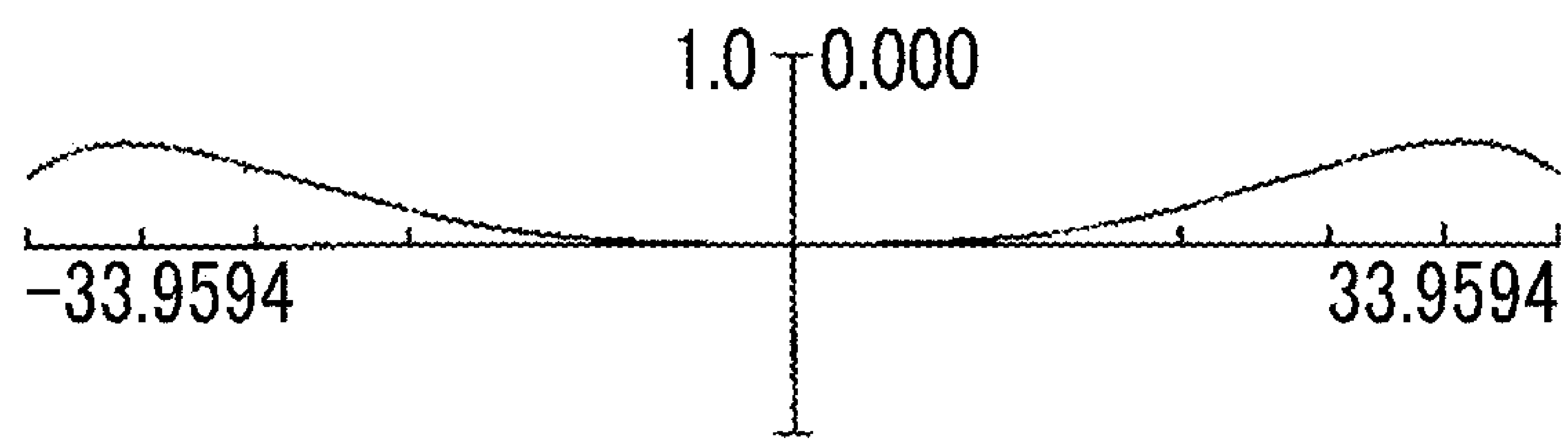


FIG. 11C

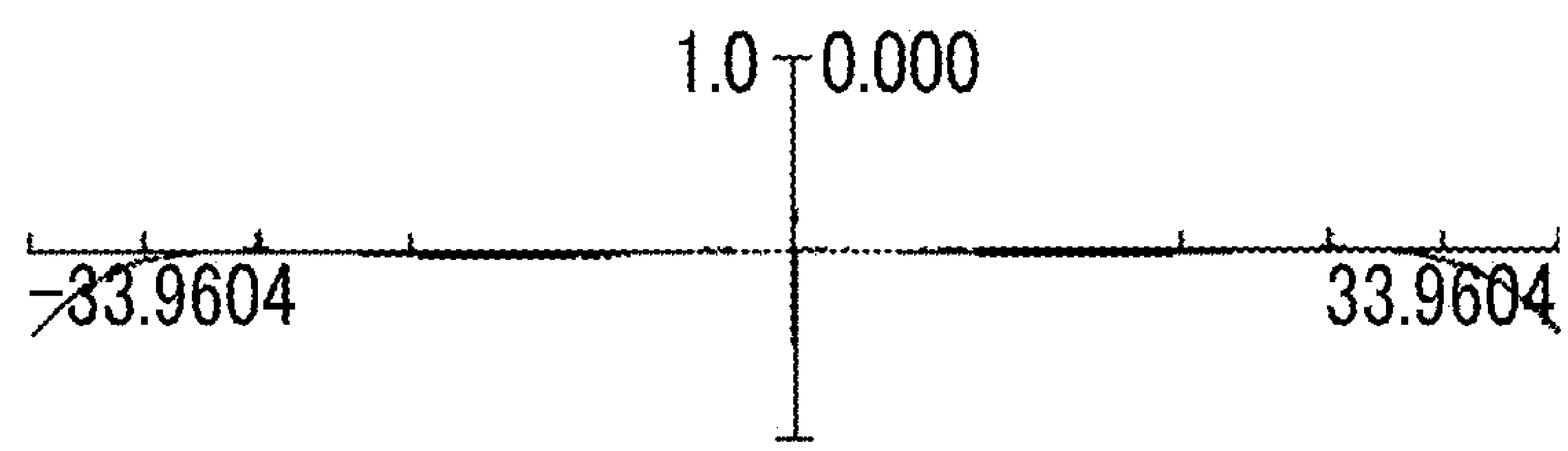


FIG. 11D

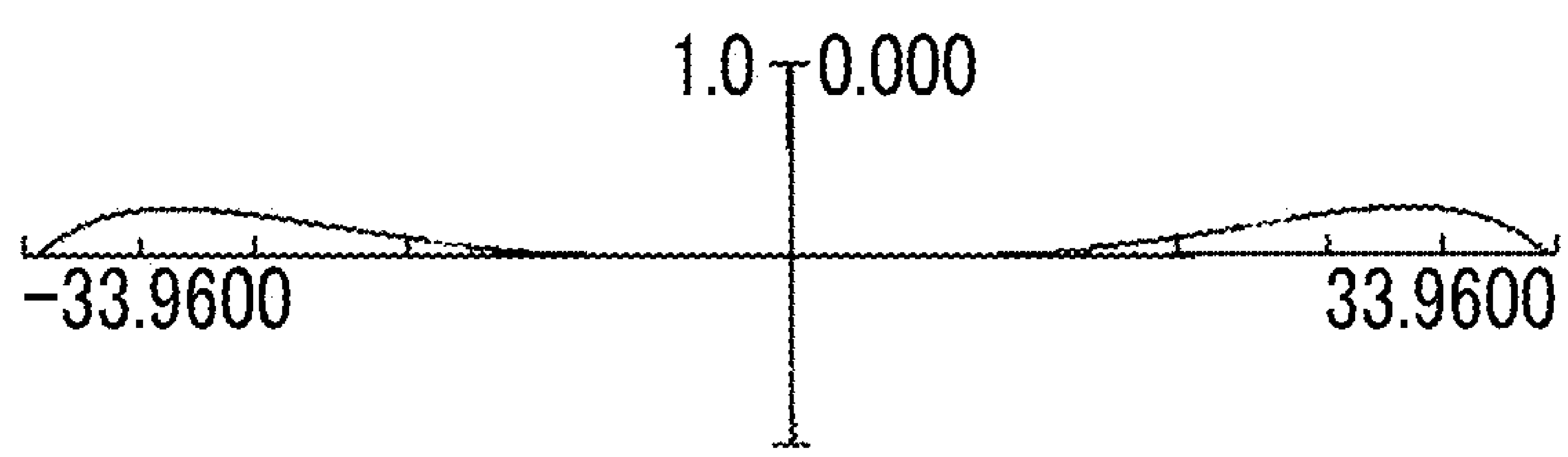


FIG. 11E

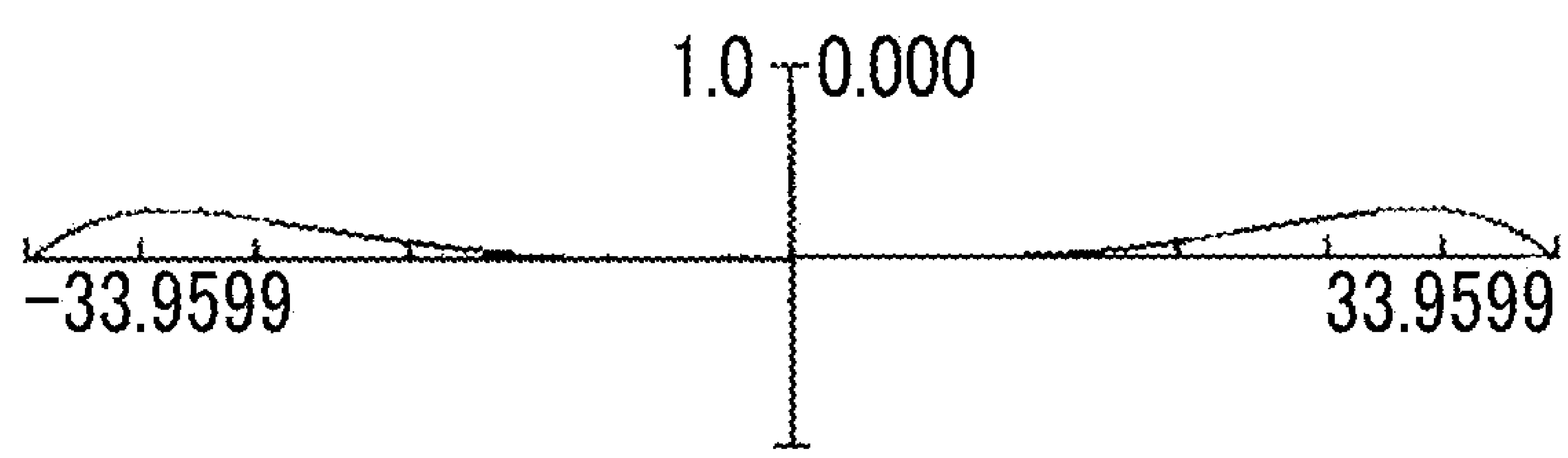


FIG. 12A

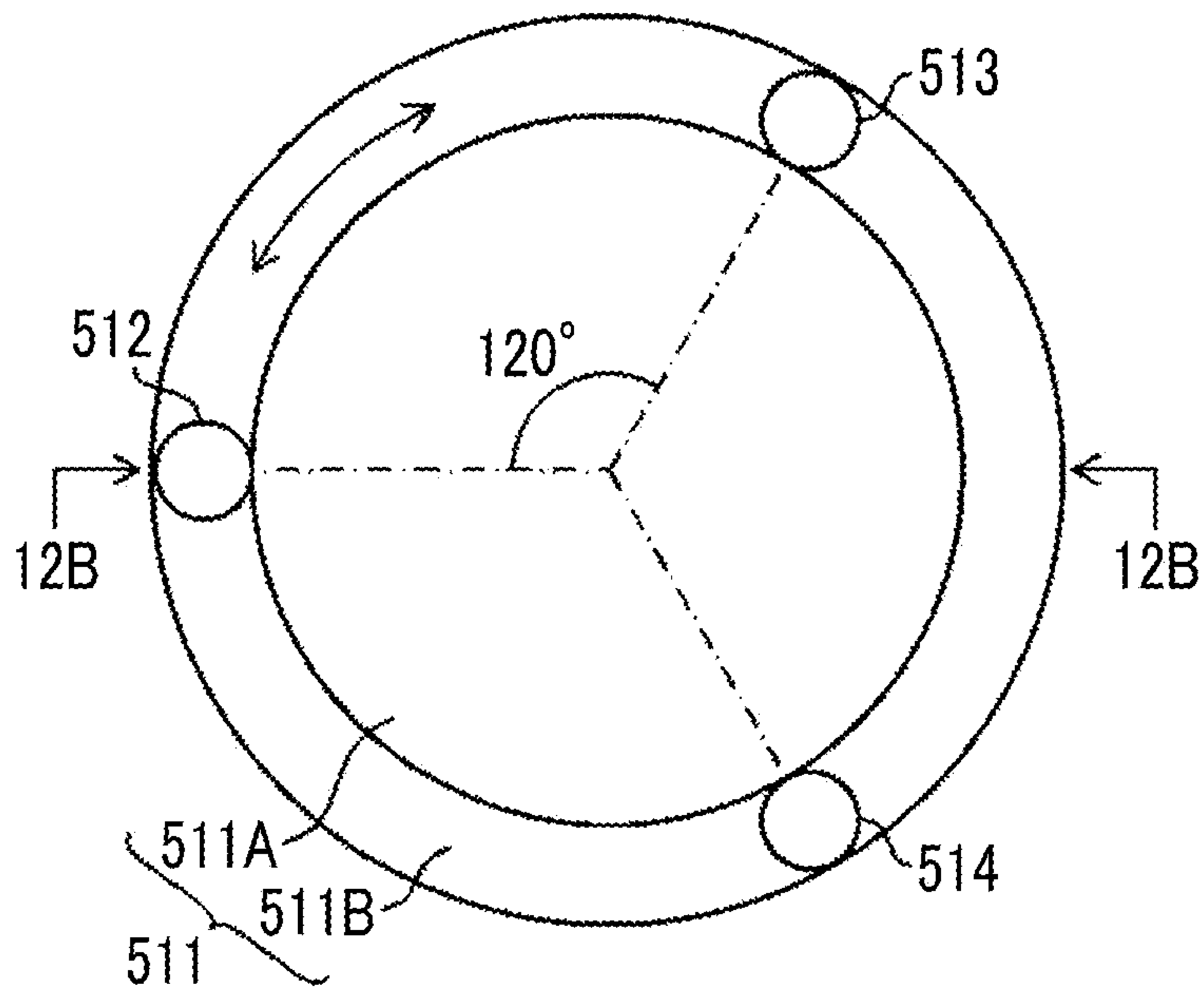


FIG. 12B

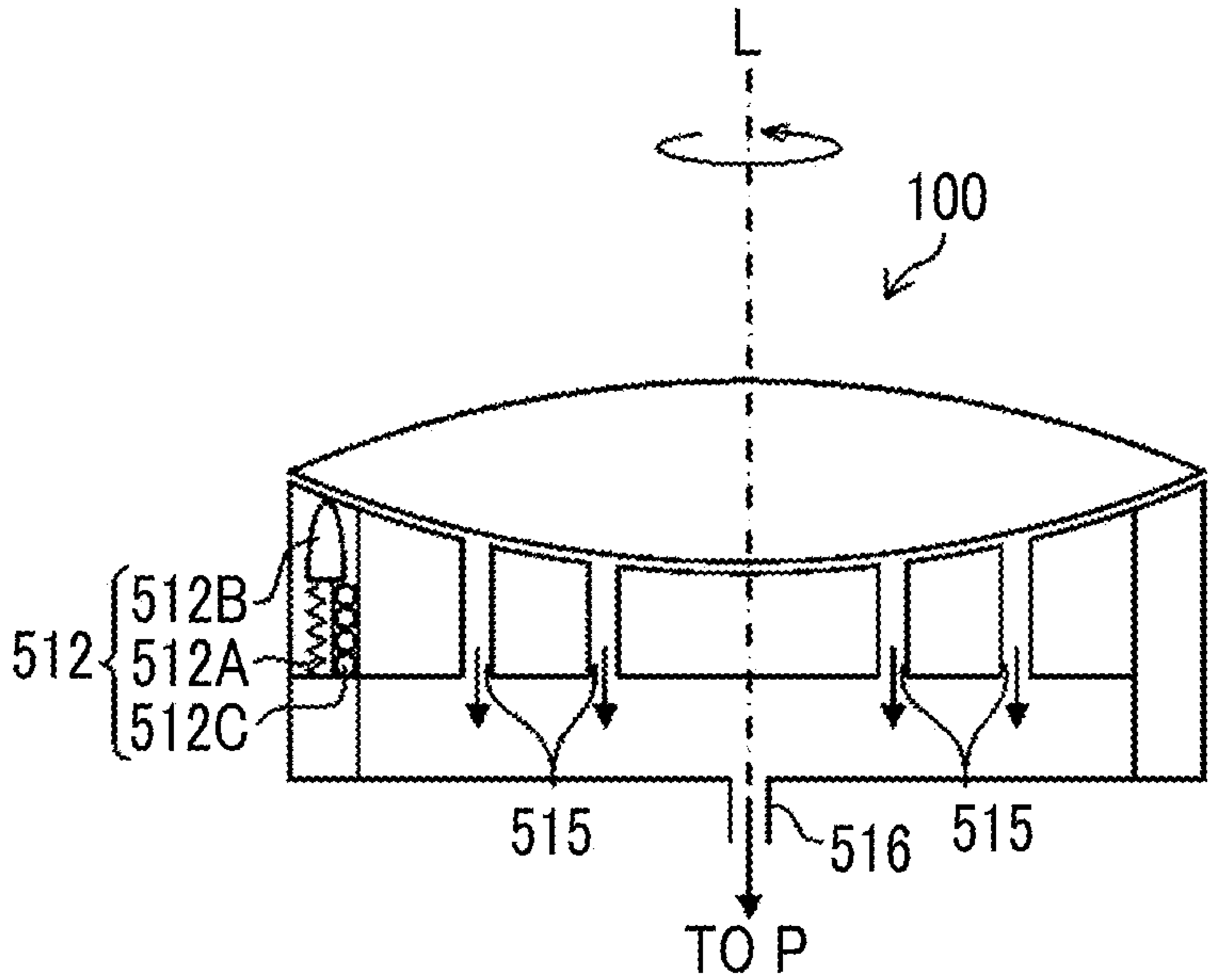
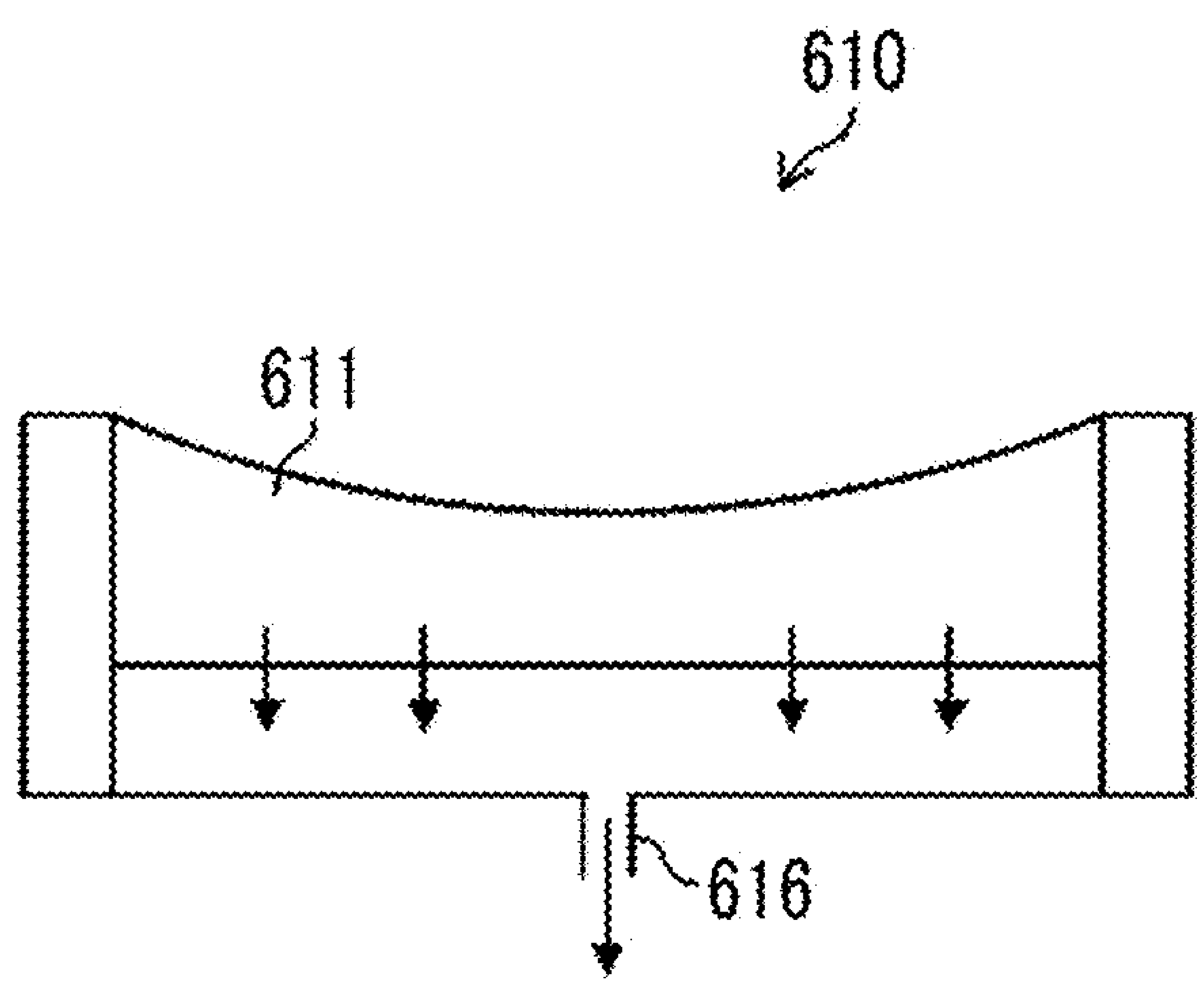


FIG. 13



LENS MANUFACTURING METHOD

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is a Continuation of PCT International Application No. PCT/JP2015/070567 filed on Jul. 17, 2015 claiming priority under 35 U.S.C §119(a) to Japanese Patent Application No. 2014-202531 filed on Sep. 30, 2014. Each of the above applications is hereby expressly incorporated by reference, in their entirety, into the present application.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a lens manufacturing method, a lens, and a lens holding device, and particularly, to a lens manufacturing method for grinding and polishing a lens, a lens manufactured through grinding and polishing, and a lens holding device used for manufacturing such a lens.

2. Description of the Related Art

When objects to be machined, such as lenses or semiconductor wafers, are grinded and polished, an object to be machined is fixed by bonding a reverse surface of the object to be machined to a holding fixture (jig) or suctioning the reverse surface of the object to be machined via the holding fixture, and a surface to be machined is machined using a machining machine in the fixed state.

For example, JP2000-79547A describes that an adhesive is used or a reverse surface is suctioned when a lens is attached to a jig for lens polishing. Additionally, JP2002-126960A describes that a lens is suctioned by a number of suction ports when a lens is polished, and JP1996-323571A (JP-H08-323571A) and JP2005-118979A describe that a planar semiconductor wafer is suctioned via a porous body or a number of holes.

Additionally, it is known that, when an object to be machined with a generally non-planar shape such as a lens is fixed to the holding fixture, the shape of a holding surface of the holding fixture imitates the shape of a reverse surface of the object to be machined. For example, JP2003-334748A describes that a lens reverse surface is fixed to a fixture via a low melting alloy, and JP2013-180372A and JP2013-180373A describe that a lens holding member having plasticity or shape memory properties is deformed according to the shape of a reverse surface of a lens.

SUMMARY OF THE INVENTION

In recent years, making an image finer is advancing in movies, television broadcasting, or the like. Along with this, sensors that capture such a high-definition image are also made to increase the number of pixels, and pixel size becomes small. For this reason, the accuracy required of an optical system is also made very high. For example, in ordinary spherical lenses, a saddle-type error (a so-called astigmatism error) may be generated in a planar shape, and aberration is generated in a transmission wave surface due to a difference in surface shape accuracy from a reverse surface. It is expected from now on that an allowable value of this astigmatism error is 0.1 μm or less.

However, in the above-described related-art techniques, it was difficult to machine non-planar lenses along with both surfaces with high accuracy.

For example, in the technique described in the above JP2000-79547A, simply when positioning being performed by a positioning member, the lens is held and fixed with an error of the reverse surface of the lens being indwelled, and a relative surface shape error occurs on the front and reverse surface of the lens. Additionally, in JP2002-126960A, the lens reverse surface (a surface opposite to the surface to be machined) is a plane, and cannot be applied in a case where the reverse surface and the lens holding surface of the holding fixture are non-planes. Also in JP1996-323571A (JP-H08-323571A) and JP2005-118979A, the object to be machined such as a semiconductor wafer is planar, and cannot be applied in a case where the reverse surface and the lens holding surface of the holding fixture are non-planes. Moreover, in all of JP2003-334748A, JP2013-180372A, and JP2013-180373A, the holding is made in a state where (the holding surface of) the holding fixture has imitated the shape of the reverse surface of the lens (the shape of the holding surface is deformed according to the lens reverse surface, and the shape itself of the reverse surface of the lens does not vary). In a case where an error (surface shape error) is in the lens reverse surface, the holding is made with the error being indwelled. For this reason, in a case where a front surface that is an opposite surface (a surface to be machined) of the lens held in this way is grinded or polished, the surface shape of the surface to be machined (front surface) is machined with the accuracy of the machining machine. Therefore, a relative error occurs on the front and reverse surfaces of the lens detached from the holding fixture. As a result, an optical transmission wave surface will have aberration.

The invention has been made in view of such circumstances, and an object thereof is to provide a lens manufacturing method that can manufacture a lens having excellent optical transmission performance, a lens having excellent optical transmission performance, and a lens holding device used for manufacturing such a lens.

In order to achieve the above object, a lens manufacturing method according to a first aspect of the invention is a lens manufacturing method comprising a holding step of holding a lens in a lens holding fixture, and a machining step of machining a surface to be machined in the held lens. A reverse surface of the surface to be machined is machined into a non-planar shape with a first surface shape error. A lens holding surface of the lens holding fixture is machined into the same shape as the non-planar shape with a second surface shape error smaller than the first surface shape error. In the holding step, the reverse surface is brought into surface contact with the lens holding surface in imitation of the lens holding surface to correct the shape of the lens such that the reverse surface runs along the lens holding surface. In the machining step, the surface to be machined is machined in a state where the correction has been made by the holding step.

According to the first aspect of the invention, by bringing the reverse surface of the lens having the first surface shape error into surface contact with the lens holding surface having the second surface shape error smaller than the first surface shape error in imitation of the lens holding surface, the shape (the front surface and the reverse surface) of the lens is corrected (deformed by a difference between the first surface shape error and the second surface shape error), and the surface to be machined is machined in this corrected state. Accordingly, the surface to be machined (front surface) in the lens is machined with machining accuracy determined depending on a distance between a machining tool and a lens holding surface (or the reverse surface of the held lens) of the lens holding fixture. If the machining is completed and the lens is removed from the holding fixture, the corrected state is completed and the lens reverse surface returns (is deformed) to its original shape (a state having the first surface shape error). However, the surface to be machined is also deformed in the same direction as the reverse surface by the "difference between the first surface shape error and the second surface shape error" due to the completion of the corrected state (in addition, in a case where the second surface shape error is very small compared to the first surface shape error, any one of the surfaces may be considered to be deformed by the first surface shape error). That is, since the same surface shape error (first surface shape error) occurs in the same direction as the thickness direction (a front and reverse surface direction) of the lens on the front surface and the reverse surface, the first surface shape errors are offset from each other on the reverse surface and the front surface of the lens, and a lens thickness error becomes small. As a result, a lens (a lens having excellent optical transmission performance) with a small transmission wave surface aberration can be manufactured.

In addition, in the first aspect and the following respective aspects, the "non-planar shape" may be a spherical shape or may be an aspheric shape. Additionally, as a case where the lens reverse surface and a lens holding surface have "the same shape", for example, cases where both surfaces are spherical surfaces with the same radius, and the same paraboloidal surfaces, elliptical surface, the same hyperboloidal surfaces, and the same high-order polynomial surfaces are included.

In the lens manufacturing method related to a second aspect based on the first aspect, an aligning step of performing alignment of the reverse surface and the lens holding surface is further comprised, and the holding step is performed after the aligning step. The machining error of the lens can be made small by performing the alignment.

In the lens manufacturing method related to a third aspect based on the first or second aspect, in the aligning step, the alignment is performed by placing the reverse surface on an elastic holding member installed at a peripheral edge portion of the lens holding surface. In this aspect, the correction of the lens shape is kept from being influenced by placing the reverse surface on the elastic holding member installed at the peripheral portion of the lens holding surface to perform the alignment.

In the lens manufacturing method related to a fourth aspect based on any one of the first to third aspects, the elastic holding member is installed outside an effective diameter of the reverse surface. Since the elastic holding member is installed outside the effective diameter of the reverse surface, the influence exerted on the correction of the lens shape is made less. In addition, in a fourth aspect, the outside of a diameter to be machined, an outer peripheral portion (peripheral edge portion) held by the holding member at the time of the attachment to a lens barrel, or the like can be "outside the effective diameter".

In the lens manufacturing method related to a fifth aspect based on any one of the first to fourth aspects, in the aligning step, the center of the lens and the center of the lens holding fixture are aligned with each other.

In the lens manufacturing method related to a sixth aspect based on any one of the first to fifth aspects, in the holding step, the correction is performed by suctioning the reverse surface via the lens holding fixture to make the reverse surface imitate the lens holding surface. By suctioning the reverse surface via the holding fixture, the reverse surface is held by the holding fixture in a state where the lens shape is corrected.

In the lens manufacturing method related to a seventh aspect based on any one of the first to sixth aspects, the second surface shape error is ½ or less of an allowable value (for example, a PV value 0.3 μm) of a thickness distribution error of the lens. In addition, in the seventh aspect, it is more preferable that the second surface shape error is ⅕ or less of the allowable value of the thickness distribution error of the lens.

In the lens manufacturing method related to an eighth aspect based on any one of the first to seventh aspects, the first surface shape error and the second surface shape error are specified by a PV value. In addition, the PV value (Peak-to-Valley Value) is a maximum error of a shape with respect to a design value of a machined surface, that is, a difference between a highest point (Peak) and a lowest point (Valley) within a measuring range, and is widely used for expressing the shape accuracy of an optical member.

A lens related to a ninth aspect of the invention is manufactured by the lens manufacturing method according to any one of the first to eighth aspects. Since the lens is manufactured by the lens manufacturing method according to any one of the first to eighth aspects, the surface shape errors are offset from each other on the reverse surface and the front surface of the lens, and a lens thickness error becomes small. As a result, a lens (a lens having excellent optical transmission performance) with a small transmission wave surface aberration is obtained.

In order to achieve the above object, a lens related to a tenth aspect of the invention is a lens having a front surface and a reverse surface machined into a non-planar shape. A surface shape error of the front surface is offset by a surface shape error of the reverse surface. Accordingly, the surface shape errors are offset from each other on the reverse surface and the front surface of the lens, and thereby, the lens thickness error becomes small. As a result, a lens (a lens having excellent optical transmission performance) with a small transmission wave surface aberration is obtained.

In the lens related to an eleventh aspect of the invention based on the tenth aspect, the surface shape error of the front surface and the surface shape error of the reverse surface have the same size, and occur in the same direction as a thickness direction of the lens. In the eleventh aspect, the offset of the surface shape errors in the above tenth aspect is specifically described.

In order to achieve the above object, a lens holding device related to a twelfth aspect of the invention is a lens holding device comprising a lens holding fixture that holds a lens; and a correction unit that corrects the shape of the lens such that a surface to be held in the lens runs along a lens holding surface of the lens holding fixture. The lens holding surface and the surface to be held are machined into the same non-planar shape. A surface shape error of the lens holding surface is smaller than a surface shape error of the surface to be held. The correction unit brings the surface to be held into surface contact with the lens holding surface in imitation of the lens holding surface to perform correction. The twelfth aspect specifies the invention of the lens holding device corresponding to the lens manufacturing method related to the first aspect, and a lens (a lens having excellent optical transmission performance) with small transmission wave surface aberration can be manufactured by using this lens holding device.

In the lens manufacturing device related to a thirteenth aspect based on the twelfth aspect, the surface shape error of the lens holding surface and the surface shape error of the surface to be held are specified by a PV value. The meaning of the PV value is the same as the above-described one of the eighth aspect.

According to the lens manufacturing method, the lens, and the lens holding device of the invention, a lens having excellent optical transmission performance can be obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an external view illustrating a lens manufacturing apparatus related to an embodiment of the invention.

FIGS. **2**A to **2**D illustrate a lens holding fixture related to the embodiment of the invention, FIG. **2**A is a plan view, FIG. **2**B is a cross sectional view, and FIGS. **2**C, and **2**D are partial sectional views.

FIG. **3** is a flowchart illustrating a lens manufacturing method related to the embodiment of the invention.

FIG. **4** is a view illustrating an aspect of the lens manufacturing method related to the embodiment of the invention.

FIGS. **5**A and **5**B are views illustrating an example of an astigmatism error, FIG. **5**A is a perspective view, and FIG. **5**B is a plan view.

FIG. **6** is a view illustrating an aspect of lens machining according to one example of the invention.

FIG. **7** is a view illustrating an aspect of a comparative example of the lens machining.

FIG. **8** is a view illustrating an aspect of another comparative examples of the lens machining.

FIG. **9** is a table illustrating machining conditions and machining results according to the example and comparative examples of the lens machining according to the invention.

FIG. **10** is a cross sectional view illustrating the configuration of a television lens, and a lens to be machined in the television lens.

FIGS. **11**A to **11**E are views illustrating results obtained when wave aberrations of the lens to be machined illustrated in FIG. **10** are simulated.

FIGS. **12**A and **12**B are view illustrating another aspect of the lens holding fixture, FIG. **12**A is a plan view, and FIG. **12**B is a cross sectional view.

FIG. **13** is a view illustrating still another aspect of the lens holding fixture.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Hereinafter, embodiments of a lens manufacturing method, a lens, and a lens holding device related to the invention will be described with respect to the accompanying drawings.

<Configuration of Lens Manufacturing Apparatus>

FIG. **1** is a view illustrating the configuration of main parts of a lens manufacturing apparatus **10** (including the lens holding device) to which an embodiment of the invention is applied. The lens manufacturing apparatus **10** is constituted by a lens holding fixture (holding fixture) **110**, a pump **122** (correction unit), a motor **124**, a controller **126** (correction unit), a push-out tool **132**, a measurement pick **134**, and a grindstone **142**, and a power supply device (not illustrated) in addition to these.

The lens holding fixture **110** suctions and holds a lens **100** via the pump **122** and is rotated about an axis L by the motor **124**. Control for the suction, the holding, and the rotation is performed by the controller **126**. The push-out tool **132** is configured to be movable forward and backward in a direction passing through the center of the lens holding fixture **110**, and is adapted to be able to push a side surface of the lens **100** placed on the lens holding fixture **110**. The measurement pick **134** is adapted to be disposed outside the lens **100** and the lens holding fixture **110** and be able to detect any contact with the lens **100**, and the alignment between the lens **100** and the lens holding fixture **110** is performed by the push-out tool **132** and the measurement pick **134**.

The details of lens machining using the lens manufacturing apparatus **10** will be described below.

<Configuration of Lens Holding Fixture>

FIGS. **2**A to **2**D are views illustrating the configuration of the lens holding fixture **110**, FIG. **2**A is a plan view, FIG. **2**B is a cross sectional view in a direction **2**B-**2**B of FIG. **2**A.

<Elastic Holding Member>

As illustrated in FIG. **2**A, a lens holding surface **111** of the lens holding fixture **110** is divided into a region **111**A that is a center portion and a region **111**B that is a peripheral edge portion. The region **111**A is a region corresponding to the effective diameter (diameter r_0) of a reverse surface **100**A of the lens **100**, and the region **111**B (diameter $r_1 > r_0$) is a region outside the effective diameter of the reverse surface **100**A. Here, the effective diameter is the diameter of parallel pencil of rays that exit from infinity object point on the optical axis of a lens and pass through the lens. In the region **111**B, the elastic holding members **112**, **113**, and **114** are disposed so as to form an angle of 120° mutually with respect to a center O of the lens holding surface **111**.

The elastic holding member **112** consists of a spring **112**A and a head **112**B, and the head **112**B protrudes to an upper part of the region **111**B, as illustrated in FIG. **2**C, in a state where the suction of the lens **100** is not performed. Then, if the lens **100** is suctioned as will be described below, as illustrated in FIG. **2**D, the spring **112**A is pushed and compressed by the reverse surface **100**A of the lens **100**, and an upper end of the head **112**B is located on the surface of the region **111**B. Then, if the suction of the lens **100** is completed and the lens **100** is detached from the lens holding fixture **110**, the elastic holding member **112** is returned back to a state as illustrated in FIG. **2**C by the elastic force of the spring **112**A.

Since the structure and working of the elastic holding members **113** and **114** are the same as those of the elastic holding member **112**, the description thereof will be omitted.

<Hole and Suction Port>

The lens holding fixture **110** is provided with a plurality of holes **115** passing therethrough in a vertical direction from the lens holding surface **111**. The holes **115** communicate with a suction port **116** in a lower part of the lens holding fixture **110**, and suction the reverse surface **100**A of the lens **100** via the holes **115** and the suction port **116** during lens holding.

<Procedure of Lens Machining>

Next, a lens manufacturing method using the lens manufacturing apparatus **10** related to the present embodiment will be described. FIG. **3** is a flowchart illustrating a procedure of such a lens manufacturing method (lens machining method), and FIG. **4** is a conceptual diagram illustrating an aspect of a lens error during the lens machining. Additionally, FIGS. **5**A and **5**B are views illustrating an example of an astigmatism error. In addition, in FIG. **4** and its subsequent drawings, dotted lines represents errors in an X-axis direction, and one-dot chain lines represents errors in a Y-axis direction.

First, the lens **100** is placed on the lens holding fixture **110** (S**100**). In this state, the reverse surface **100**A is machined in a spherical shape (non-planar shape) with a radius R, and has an astigmatism error PV**1** (first surface shape error) as illustrated in FIG. **4**(*a*) and FIG. **4**(*e*). The "astigmatism" is a word having "astigmatism" as the origin of a word, and the "astigmatism error" generally means an unsymmetrical surface shape error in machining of an optical member. For example, as illustrated in FIGS. **5**A and **5**B, in a case where the astigmatism error has a surface shape error (a difference between a design value and an actual shape) that is convex downward in the X direction and is convex upward in the Y direction, it can be said to "have an astigmatism error". This astigmatism error is expressed by a PV value (Peak-to-Valley Value), that is, a maximum error (a difference between a highest point (Peak) and a lowest point (Valley) within a measuring range) with respect to a design value of a machined surface (here, the reverse surface **100**A). In the present embodiment, it is assumed that the reverse surface **100**A has the astigmatism error PV**1** as illustrated in FIG. **4**(*e*).

The above-described aspheric surface shape and astigmatism error shape can be expressed by the following Equation.

<Aspheric Surface Shape Definitional Equation (Rotation Object with Respect to Optical Axis)>

[Equation 1]

$$Z = \frac{Ch^2}{1+\sqrt{1-(1+K)\times C^2h^2}} + A4\times h^2 + A6\times h^3 + A8\times h^4 \ldots + A20\times h^{10} \tag{1}$$

<Astigmatism Shape Definitional Equation>

[Equation 2]

$$Z = \frac{\frac{x^2}{Rx}+\frac{y^2}{Ry}}{1+\sqrt{1-(1+K)\times\left(\frac{x^2}{Rx^2}+\frac{y^2}{Ry^2}\right)}} + A4\times((1-A4)\times x^2+(1+A4)\times y^2)^2 + A6\times((1-A6)\times x^2+(1+A6)\times y^2)^3 + A8\times((1-A8)\times x^2+(1+A8)\times y^2)^4 + \vdots\; A20\times((1-A20)\times x^2+(1+A20)\times y^2)^{10} \tag{2}$$

Here, C is an inverse number of the paraxial curvature radius of a lens, h is the height from the optical axis, K is a cone constant, and A**4** to A**20** are aspheric surface coefficients. In the case of a spherical surface, K=0 and A**4** to A**20**=0.

In addition, as illustrated in FIGS. **4**(*f*) and **4**(*g*), the lens holding surface (holding surface) **111** of the lens holding fixture **110** is machined in a spherical shape (non-planar shape) with the radius R at an astigmatism error PV**2** (<PV**1**; second surface shape error) (that is, the lens holding surface **111** is machined into the same shape as the reverse surface **100**A at the astigmatism error PV**2** smaller than the astigmatism error PV**1** of the reverse surface **100**A of the lens **100**).

In addition, in S**100**, as described above, the reverse surface **100**A of the lens **100** is held to abuts against the elastic holding members **112**, **113**, and **114** (refer to FIGS. **2**B and **2**C).

Next, alignment (aligning step) of the lens **100** and the lens holding fixture **110** is performed (S**110**). This alignment is performed by pushing the side surface (end part) of the lens **100** with the push-out tool **132** as described above, and it can be seen that, if a suitable amount of push-out is reached, an opposite side surface of the lens **100** touches the measurement pick **134**, the measurement pick **134** fluctuates, a signal showing the fluctuation is output, and the amount of push-out becomes suitable. In a case where the amount of push-out is excessive, the lens holding fixture **110** has only to be half-rotated by the motor **124** and the controller **126** to push out the opposite side surface. By repeating the push-out in this way while the lens holding fixture **110** is rotated appropriately, the alignment can be performed, and the center of the lens **100** and the center of the lens holding fixture **110** can be matched with each other.

If the alignment is performed in S**110**, the lens **100** is held by the lens holding fixture **110** in an aligned state (S**120**; holding step). The holding of the lens **100** is performed by suctioning the reverse surface **100**A of the lens **100** via the holes **115** and the suction port **116** using the pump **122** and the controller **126**, as described above. Then, by suctioning the reverse surface **100**A in this way, the shape of the reverse surface **100**A comes into surface contact with the lens holding surface **111** of the lens holding fixture **110** in imitation of the lens holding surface **111**. Accordingly, the shape of the lens **100** is corrected (deformed) such that the reverse surface **100**A having the astigmatism error PV**1** runs along the lens holding surface **111** having the astigmatism error PV**2** (<PV**1**) (refer to FIG. **4**(*b*)). That is, the reverse surface **100**A is deformed by a difference between the astigmatism error PV**1** and the astigmatism error PV**2**.

Such holding continues being performed until the machining (grinding and polishing) of the lens **100** is completed.

If the lens **100** is held, grinding and polishing is performed (S**130**; machining step). This grinding and polishing is performed by moving a front surface **100**B (surface to be machined) of the lens **100**, rotating the grindstone **142** using a motor (not illustrated) as illustrated in FIG. **4**(*c*) while the lens holding fixture **110** is rotated by the motor **124** and the controller **126**. In addition, since the lens holding fixture **110** is rotating, it is not necessary to perform grinding and polishing from an outer peripheral part of the front surface **100**B to an opposite outer peripheral part, and grinding and polishing has only to be repeated from one outer peripheral part to the center (or from the center to the outer peripheral part). The front surface **100**B is machined with machining accuracy depending on the distance accuracy between the grindstone **142** and the lens holding surface **111** (or held reverse surface **100**A) of the lens holding fixture **110** by such grinding and polishing.

After the grinding and polishing of S**130** is completed, the rotation of the lens holding fixture **110** is stopped, suction of the reverse surface **100**A is stopped and the lens **100** is separated from the lens holding fixture **110** (S**140**). Then, as illustrated in FIG. **4**(*d*) and FIG. **4**(*h*), during the suctioning and holding, the reverse surface **100**A that has imitated the lens holding surface **111** returns to its original shape, and has the astigmatism error PV**1** (PV value). However, simultaneously with this, the front surface **100**B is also deformed in the same direction as the reverse surface **100**A and is deformed by the "difference between the astigmatism error PV**1** and the astigmatism error PV**2**" (refer to FIG. **4**(*i*)). Hence, since the same astigmatism errors (surface shape errors) PV**1** occur in the same direction with respect to a thickness direction (a front and reverse surface direction) of a lens on the reverse surface **100**A and the front surface **100**B, the astigmatism errors PV**1** are offset from each other on the reverse surface **100**A and the front surface **100**B.

As described above, according to the lens manufacturing apparatus **10**, the lens holding fixture **110**, and the lens manufacturing method related to the present embodiment, a lens **100** with a small surface shape error and a small transmission wave surface aberration (a lens having excellent optical transmission performance) can be obtained.

EXAMPLE AND COMPARATIVE EXAMPLES

Next, the lens manufacturing apparatus **10**, the lens **100**, the lens holding fixture **110**, and the lens manufacturing method related to the above embodiment will be described, showing specific numerical values using an example and comparative examples. The conditions of the example and Comparative Examples 1 and 2 are as follows.

Example

Surface shape error of lens reverse surface (astigmatism error: PV value): 150 nm

Surface shape error of lens holding fixture (astigmatism error: PV value): 30 nm

Comparative Example 1

Surface shape error of lens reverse surface (astigmatism error: PV value): 50 nm

Surface shape error of lens holding fixture (astigmatism error: PV value): 200 nm

Comparative Example 2

Surface shape error of lens reverse surface (astigmatism error: PV value): 180 nm

Surface shape error of lens holding fixture (astigmatism error: PV value): 30 nm

The above example is an example in a case where (Surface shape error of lens reverse surface<Surface shape error of lens holding fixture) is satisfied, that is, the reverse surface error is corrected by the holding fixture, that is, the conditions of the invention are satisfied, and Comparative example 1 is an example in a case where (Surface shape error of lens reverse surface>Surface shape error of lens holding fixture) is satisfied, that is, the conditions of the invention are not satisfied. Additionally, Comparative Example 2 is a case where (Surface shape error of lens reverse surface<Surface shape error of lens holding fixture) is satisfied but the surface shape error of the lens reverse surface is not corrected by the lens holding fixture (for example, a case according to a related-art holding method such that a lens is bonded at an outer peripheral part of the lens by the lens holding fixture).

FIG. **6** is a view illustrating an aspect of the lens machining in the above example and an error in that case. A reverse surface of a lens **200** related to the present example, has an astigmatism error PV**3**A (refer to FIG. **6**(*a*) and FIG. **6**(*j*)), and a lens holding surface of a lens holding fixture **210** has an astigmatism error PV**3**B (refer to FIG. **6**(*i*) and FIG. **6**(*k*)). If the lens **200** is suctioned and held by the lens holding fixture **210** (refer to FIG. **6**(*b*)), the shape of the lens **200** is corrected by the lens holding fixture **210**, and is deformed as illustrated in FIG. **6**(*f*). Then, if the surface of the lens **200** is machined (grinded, polished) as illustrated in FIG. **6**(*c*), a front surface of the lens **200** is brought into a state where this front surface has a machining error as illustrated in FIG. **6**(*g*). Then, if the machining is completed and the lens **200** is separated from the lens holding fixture **210** (refer to FIG. **6**(*d*)), the reverse surface of the lens **200** returns to a state having the astigmatism error PV**3**A similar to before the suctioning and the holding (refer to FIG. **6**(*l*)), and a state where this astigmatism error PV**3**A is also added to the front surface of the lens **200** is brought about.

Hence, astigmatism errors PV**3**A are offset from each other at the front surface and the reverse surface of the lens **200** similar to the above-described embodiment by the above machining. In addition, FIG. **6**(*e*), FIG. **6**(*f*), FIG. **6**(*g*), and FIG. **6**(*h*) respectively illustrate a state where the front surface of the lens **200** has an initial error, a state where the front surface is deformed due to the suctioning and holding and the error also has varied, a state where the front surface has an error caused by machining, and a state where the astigmatism error PV**3**A is added to the machining error.

FIG. **7** is a view illustrating a machining state in the above Comparative Example 1. In Comparative Example 1, a lens **300** is machined using a lens holding fixture **310**, and finally, astigmatism errors PV**4**A are offset from each other at a front surface and a reverse surface of the lens **300**. Since meanings of FIG. **7**(*a*) to FIG. **7**(*l*) are the same as those of FIG. **6**(*a*) to FIG. **6**(*l*), the detailed description thereof will be omitted.

FIG. **8** is a view illustrating a machining state in the above Comparative Example 2. In Comparative Example 2, a lens **400** is machined using a lens holding fixture **410**. The astigmatism error of the reverse surface of the lens **400** is PVSA, and the error of the lens holding fixture **410** is PV**5**B (<PV**5**A). Since meanings of FIG. **8**(*a*) to FIG. **8**(*l*) are the same as those of FIG. **6**(*a*) to FIG. **6**(*l*), the detailed description thereof will be omitted.

FIG. **9** illustrates a table obtained when the machining results of the above example and Comparative Examples 1 and 2 are summarized. As illustrated in FIG. **9**, in the example in which the surface shape error of the lens holding fixture is smaller than the astigmatism error of the lens reverse surface and the lens reverse surface is corrected by the lens holding fixture, the transmission wave surface aberration is as small as 25 nm. However, in Comparative Example 1 in which the surface shape error of the lens holding fixture is larger than the astigmatism error on the lens reverse surface and the transmission wave surface aberration is 190 nm and has a larger value as compared to the example. Additionally, in Comparative Example 2 in which the surface shape error of the lens holding fixture is smaller than the astigmatism error of the lens reverse surface and the lens reverse surface is not corrected by the lens holding fixture, astigmatism errors PV**5**A are not offset from each other at the front surface and the reverse surface of the lens **400**, and the transmission wave surface aberration has a larger value (140 nm) as compared to the example.

In this way, according to the invention, it can be seen that a lens with a small transmission wave surface aberration (a lens having excellent optical transmission performance) can be obtained.

<Simulation Result>

Next, results obtained when the lens manufacturing method of the invention is simulated are illustrated. FIG. **10** is a cross sectional view illustrating the configuration of a television lens **700**, and a second lens **710** that is an object to be machined. In the present simulation, in a case where there is an astigmatism error in a reverse surface **710**A (a fourth surface when a left surface of a first lens is a first surface; a spherical shape) of the second lens **710** in FIG. **10**, influences on lens performance in cases where a front surface **710**B is polished by a related-art lens manufacturing method (polishing method) and the lens manufacturing method of the invention are compared with each other using wave aberrations.

FIGS. **11**A to **11**E are views illustrating simulation results of imaging performance on an optical axis when using the lens of FIG. **10**. In FIGS. **11**A to FIG. **11**E, a horizontal axis represents entrance pupil diameter (unit: mm) calculated by "Focal distance/f number", and a vertical axis represents the size (a reference wavelength 1.0λ; here, showing the wavelength of an e line (a spectral line of mercury with a wavelength of about 546 nm)) of wave aberration. FIG. **11**A illustrates design values and wave aberrations occur in a positive (+) direction at a lens peripheral portion. In the design values, the wave aberrations are the same (symmetrical) irrespective of direction.

FIGS. **11**B and **11**C illustrate results obtained by the related-art polishing method. In the case of the related-art polishing method, the front surface **710**B and the reverse surface **710**A are machined independently. Therefore, the machining error of the reverse surface **710**A remains even in a case where the front surface **710**B is machined according to design values. FIG. **11**B illustrates wave aberrations in a case where +3 shape errors are given in the X direction of the reverse surface **710**A, and larger wave aberrations than the design values occur in the positive (+) direction at the lens peripheral portion. On the other hand, FIG. **11**C illustrates wave aberrations in a case where −3 shape errors are given in the Y direction of the reverse surface **710**A, and wave aberrations occur in a negative (+) direction at the lens peripheral portion. That is, in the related-art polishing method, it can be seen that the astigmatism error of the reverse surface **710**A is generated on sides of an image surface that are different from each other in the X direction and in the Y direction, and the lens performance (wave aberrations) is affected.

In contrast, in the case of the manufacturing method of the invention, the machining error of the reverse surface **710**A is generated as a machining error of the front surface **710**B as it is. In FIGS. **11**D and **11**E, the manufacturing method of the invention is applied, and the machining error of the reverse surface **710**A and the machining error of the front surface **710**B become an equal amount. That is, wave aberrations in a case where +3 shape errors are given to the reverse surface **710**A and the front surface **710**B in the X direction, respectively, and similarly −3 shape errors are given thereto in the Y direction are illustrated. Although the wave aberrations occur in the positive (+) direction at the lens peripheral portions of both the front and reverse surfaces, the aberrations are symmetrical in the X direction and in the Y direction, do not have a difference in size, either, and are as being designed. That is, according to the invention, it can be seen that even an astigmatism error in the reverse surface **710**A is offset by that in the front surface **710**B and the lens performance (wave aberrations) is not influenced. In addition, as for the signs of the above machining error, a case where a surface shape is deformed to an image side with respect to design values is defined as the positive, and a case where the surface shape is deformed to an object side is defined as the negative.

<Other Forms of Lens Holding Fixture>

Next, other forms of the lens holding fixture will be described. In the above-described embodiment and example, an aspect in which the lens holding fixture **110** includes the elastic holding member **112** and the same aspect as this have been described. However, the lens holding fixture in the invention is not limited to such aspects. In addition to the above aspects, an aspect like a lens holding fixture **510** illustrated in FIGS. **12**A to **12**D is also possible.

As illustrated in a plan view of FIG. **12**A, in the lens holding fixture **510**, a main body **511** of a holding part consists of a region **511**A that is a center portion, and a region **511**B that is a peripheral edge, and the region **511**A and the region **511**B are constituted as independent members. Elastic holding members **512**, **513**, and **514** are provided in the region **511**B so as to be apart at 120° in the circumferential direction. Although the elastic holding member **512** has a spring **512**A and a head **512**B similar to the above-described elastic holding member **112**, the elastic holding member **512** further includes a bearing **512**C, and the region **511**B rotates smoothly with respect to the region **511**A by this bearing **512**C and bearings that the other elastic holding members **513** and **514** include.

In addition, as illustrated in a cross sectional view (a cross section taken along line **12**B-**12**B of FIG. **12**A) of FIG. **12**B, the lens holding fixture **510** includes a plurality of holes **515** and a suction port **516**, similar to the lens holding fixture **110**, and accordingly, is able to perform suction and hold the lens **100**.

In the lens holding fixture **510** and the above-described lens holding fixture **110**, the elastic holding members are provided in three places apart at equal intervals in the circumferential direction. However, the number and arrangement of elastic holding members are not limited to such an aspect. For example, six or more elastic holding members may be provided at equal intervals in the circumferential direction. Otherwise, not elastic holding members that perform holding substantially at one point but elastic holding members having a length in the circumferential direction or an elastic holding member covering the entire circumference of the lens holding fixture may be provided.

Additionally, in the lens holding fixture **510** and the lens holding fixture **110**, the suctioning and holding of a lens is performed by the holes and the suction port. However, as in a lens holding fixture **610** illustrated in FIG. **13**, an entire holding portion **611** may be constituted with a porous member, and suctioning and holding may be performed via a suction port **616** provided in a bottom part.

In addition, since elements, such as a pump, a motor, a controller, a push-out tool, and a measurement pick, in FIGS. **12**A to **12**D and FIG. **13** are the same as those illustrated in FIG. **1** and FIGS. **2**A to **2**D, the illustration and description thereof will be omitted.

Moreover, it is obvious that the invention is not limited to the above-described embodiment, and various modifications can be made without departing from the spirit of the invention.

EXPLANATION OF REFERENCES

- **10**: lens manufacturing apparatus
- **100**, **200**, **300**, **400**: lens
- **110**, **210**, **310**, **410**, **510**, **610**: lens holding fixture
- **111**: lens holding surface
- **112**, **113**, **114**, **512**, **513**, **514**: elastic holding member
- **115**: hole
- **116**, **616**: suction port
- **122**: pump
- **124**: motor
- **126**: controller
- **132**: push-out tool
- **134**: measurement pick
- **142**: grindstone

What is claimed is:

1. A lens manufacturing method comprising:

a holding step of holding a lens in a lens holding fixture; and

a machining step of machining a surface to be machined in the held lens,

wherein a reverse surface of the surface to be machined is machined into a non-planar shape with a first surface shape error, and a lens holding surface of the lens holding fixture is machined into the same shape as the non-planar shape with a second surface shape error smaller than the first surface shape error,

wherein, in the holding step, the reverse surface is brought into surface contact with the lens holding surface in imitation of the lens holding surface to correct the shape of the lens such that the reverse surface runs along the lens holding surface, and

wherein, in the machining step, the surface to be machined is machined in a state where the correction has been made by the holding step.

2. The lens manufacturing method according to claim 1, further comprising:

an aligning step of performing alignment of the reverse surface and the lens holding surface,

wherein the holding step is performed after the aligning step.

3. The lens manufacturing method according to claim 2, wherein, in the aligning step, the alignment is performed by placing the reverse surface on an elastic holding member installed at a peripheral edge portion of the lens holding surface.

4. The lens manufacturing method according to claim 3, wherein the elastic holding member is installed outside an effective diameter of the reverse surface.

5. The lens manufacturing method according to claim 2, wherein, in the aligning step, the center of the lens and the center of the lens holding fixture are aligned with each other.

6. The lens manufacturing method according to claim 1, wherein, in the holding step, the correction is performed by suctioning the reverse surface via the lens holding fixture to make the reverse surface imitate the lens holding surface.

7. The lens manufacturing method according to claim 1, wherein the second surface shape error is ½ or less of an allowable value of a thickness distribution error of the lens.

8. The lens manufacturing method according to claim 1, wherein the first surface shape error and the second surface shape error are specified by a PV value.

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